1-1-2010

Strategy of water pollution prevention in Taihu Lake and its effects analysis

Shuqing Yang
University of Wollongong, shuqing@uow.edu.au

P.W. Liu
South China University of Technology

Journal of Great Lakes Research 36 (2010) 150–158

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Strategy of water pollution prevention in Taihu Lake and its effects analysis

Shu-Qing Yang [a,*], Pan-Wei Liu [b]

[a] A/Prof., School of Civil, Mining and Environmental Engineering, Univ. of Wollongong, NSW 2522, Australia
[b] College of Environmental Science and Engineering, South China University of Technology, Guangzhou 510006, China

ARTICLE INFO

Article history:
Received 9 June 2009
Accepted 22 October 2009

Communicated by Ram R. Yerubandi

Index words:
By-pass canal
Pollution prevention, Algal bloom, Taihu Lake
Flood disaster control
Water supply

ABSTRACT

Taihu Lake, the third largest freshwater lake in China, is located in the Chanjiang Delta of the Yangtze River. Its waters are used by agriculture, industry and as major drinking water for several cities including Shanghai and Wuxi. The lake also is important for tourism, aquaculture and flood control. Taihu Lake and its surrounding areas are facing three major water-related threats: deteriorating water quality with inflow and runoff from its watershed; flooding during the rainy seasons; and water shortages during drier months. Noxious algae blooms are occurring with increasing frequency and water quality continues to decline. Remedial actions implemented to date have been ineffective. This paper proposes that the problems could be remedied by constructing a by-pass channel (BPC), which would divert low-quality water from the lake during low precipitation periods and allow better quality water to flow into the lake during high flow periods. This remedial action would simultaneously deal with the deteriorating water quality of Lake Taihu and maintain its water level at a desired level. A preliminary assessment of this strategy shows that, if the BPC were implemented, the water quality of Taihu Lake would be improved significantly in few years, the flood disaster would be greatly mitigated, and the water shortage problem in the basin would be alleviated.

Introduction

Taihu Lake (119°54′–120°36′N, 30°56′–31°33′E), the third largest freshwater lake in China, is located in the highly developed and densely populated Yangtze River Delta (Pu et al., 1998). The lake is shallow with an average depth of 1.89 m, a surface area of 2238 km^2, and a volume of 4.66×10^9 m^3. The annual water input averages 7.66×10^9 m^3 and the residence time of its waters is about 300 days (Zhang et al., 2008). There are over 219 inflow-rivers or tributaries (Hu et al., 2006) but only three main outflow rivers; the outflow rivers connect the lake with the Yangtze River, the East China Sea via Shanghai, and Hangzhou Bay (Fig. 1). Water flow is highly complex in this low lying area with some rivers flowing into or out of the lake year round while others have a reverse flow depending on the season (Qin et al., 2007). Rainfall is abundant with an average of 132 rainy days annually and an average annual rainfall of about 1143.5 mm. Rainfall varies seasonally with 52% of rainfall typically occurring between June and September, i.e., during the typhoon season or flood period (Table 1). Precipitation is lower from October to May and constitutes the long dry period. Water temperatures in Taihu Lake are highest during summer (July or August with an average temperature of 30.3 °C) and lowest in winter (January with an average temperature of 6.1 °C) (Qin et al., 2002).

Taihu Lake plays multifunction roles including floodwater storage, irrigation and navigation. It also serves as a major water resource for drinking, aquaculture and industrial needs, as well as being a source of entertainment and tourist interest (Jin et al., 2006). Its drainage basin extends over 37,000 km^2 and is bounded by the Yangtze River to the north, the East China Sea to the east (including Hangzhou Bay to the south) and mountainous areas to the west (see Fig. 1). While the basin accounts for 0.4% of the total area of China and 2.9% of the nation's population, it provides more than 14% of China's Gross Domestic Production (GDP). The GDP per capita is 3.5 times as much as the state average (Zhang et al., 2007) and its urbanization level ranks the first in China. This basin is vital for eastern China, where the lake water supports more than 60 million people (about 600–900 person/km^2 on average), including the water supply to cities such as Wuxi, Suzhou, and Shanghai, one of the largest cities in the world.

With the tremendous economic growth and increased population in its basin, Taihu Lake has begun to suffer from various environmental stresses, including deterioration of its water quality with increasing nutrient and other chemical inputs. The lake is becoming increasingly eutrophied and has experienced annual lake-wide cyanobacterial blooms in recent decades; this has affected the drinking water supply of surrounding cities. Before the early 1980s, the water quality was good but since the 1980s, with the increasing discharge of industrial and domestic wastewater into the lake, the water quality has deteriorated (Ye et al., 2009); total phosphorus concentrations have increased markedly (Fig. 2). Taihu Lake now receives annually approximately 30,635,000 kg total nitrogen (TN)

* Corresponding author. Tel.: +61 2 4221 3070.
E-mail address: shuqing@uow.edu.au (S.-Q. Yang).

0380-1330/$ – see front matter. Crown Copyright © 2009 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.jglr.2009.12.010

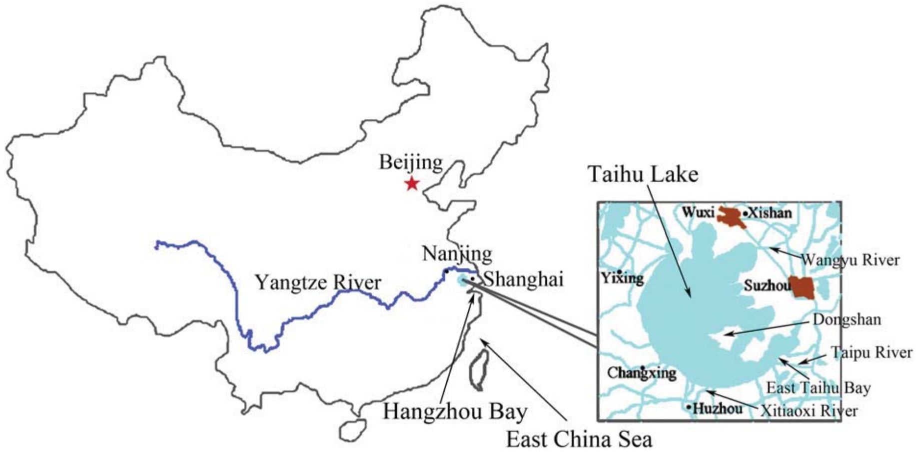

Fig. 1. Location of Taihu Lake in China after Ling et al. (2007).

and 1,751,000 kg total phosphorus (TP) from a combination of municipal and industrial wastewaters and agricultural soil runoff; chemical oxygen demand on chromium (CODCr) is 131,223,000 kg (Qin et al., 2007).

In 1990, high algae densities in Lake Taihu, which occurred over a period of 25 days, limited the ability of water works to treat intake water and 100 industries had to reduce or stop production. High algae densities also led to a large fish kill totaling 45,000 kg of dead fish. Overall, the economic losses caused by the algae bloom exceeded one hundred million Yuan (≈US$12.5 m, Ding et al., 2007). Algae blooms have continued and, in recent years, have expanded out to the lake centre. The northern and western parts of Taihu Lake are often covered by algae blooms in summer, autumn and even spring (Hu et al., 2008). In 2007, a severe algae bloom caused a drinking water contamination crisis for 4.43 million people in Wuxi City. An article in *Science* (Yang et al., 2008) reported that the concentration of dimethyl trisulfide in a water sample collected on 4 June 2007 from the drinking-water intake was 11,399 mg/l—high enough to yield strong septic and marshy odors. Over the past 20 years, considerable scientific research has been conducted and management strategies implemented in an effort to control Lake Taihu's algal blooms; a comprehensive review for the water quality in Taihu Lake can be found in Hu et al. (2006).

Apart from deteriorating water quality, Taihu Lake has two water quantity issues, i.e., too much water during high precipitation months, which causes flooding, and too little inflow during dry periods, which results in seasonal water shortages as lake level declines. During the rainy season, floods often occur and cause heavy damage such as the major flood events in 1954 and 1991. Water levels decline during the long, dry seasons leading to limitations in water supply. Water usage in the basin reaches 35.6×10^9 m^3 but the average annual water input to Taihu Lake is only 17.7×10^9 m^3 (Wu and Hu, 2008). With this large difference between supply and demand, a major proportion of the water used by industry, agriculture, and urban areas is discharged back into the water system; there generally is a concomitant deterioration in water quality. Thus, there is a need to develop a hydrological solution to control flooding to Taihu Lake while maintaining a sufficient quantity of high quality water year round. This solution must be environmentally sound.

Review of Government's Pollution Control Measures and its Effects

Since the 1980s, China has experienced the highest economic growth rate in the world; industrial development and urbanization increasingly threaten water quality of its lakes and rivers. As a result of this industrial development, China's water resources are grossly polluted by human and industrial wastes, to the point that vast stretches of rivers are dead and dying and lakes are cesspools of waste. Similarly, water quality of Taihu Lake continues to deteriorate. Guo (2007), in a *Science* article, remarked: "There's no doubt that Taihu is going to be a challenge, the degradation of the lake's water quality was a slow-motion train wreck that played out over several decades. It may take many more years to banish the blooms and bring back the Taihu beauty of yore."

Since the 1990s, China has taken a series of measures to control the pollutant discharge and to improve the water quality of Taihu Lake; since 1998, the central government has listed Taihu Lake as a top environmental priority. To this date, China has invested more than US

Table 1
Average monthly rainfall and number of rainy days in Taihu Basin.

Month	Average monthly rainfall (mm)	Average number of rainy days	Rainfall intensity (mm/day)
January	47.9	9.6	5.0
February	61.0	10.4	5.9
March	48.2	12.5	3.9
April	94.8	13.5	7.0
May	104.0	13.0	8.0
June	176.0	13.9	12.7
July	143.0	11.2	12.8
August	136.0	10.8	12.6
September	136.0	11.0	12.4
October	69.2	8.9	7.8
November	53.1	8.5	6.2
December	38.9	7.9	4.9
Annual	1143.5	131.8	8.7

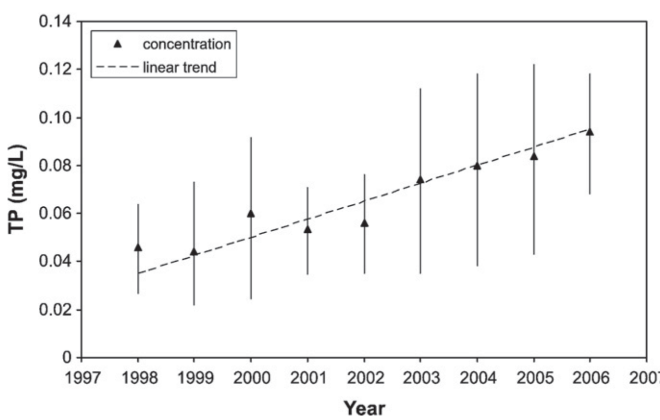

Fig. 2. Annual variation of concentration of total phosphorus (TP) in central area of Taihu Lake (after Qin et al., 2007).

$10 billion in pollution control for the lake, but there has been no significant improvement in the water quality. These management measures have included pollution reduction in industrial wastewater releases; pollution control in inflowing rivers; lakeside ecological remediation; clean-water diversion; and dredging. Highlights of these strategies are outlined below.

1) Control and reduce exogenous pollutants in the basin: stricter discharge standards for municipal wastewater treatment plants and key industries have been implemented to control pollution releases into rivers and the lake. However, the effectiveness of this strategy is limited because non-point sources contribute more than half of total pollutants entering the lake, i.e., non-point fertilizer and pesticide sources from agricultural lands. Although the government has encouraged farmers to modify farming practices to reduce fertilizer use (quantity, frequency, quality) no immediate effect of such actions has been observed and reported.
2) Water diversion from Yangtze River to the lake: since the major flood in 1991, China has invested nearly US$2 billion in construction for flood control projects for the Taihu Lake basin, including pumping stations. These pumping stations can pump Taihu Lake water and/or floodwater into Yangtze River to mitigate flood disasters, as needed. These stations also can pump water from the Yangtze River, which has an abundant flow year round, to Taihu Lake during dry periods. Numerical models by Hu et al. (2008) have shown that these water diversions from Yangtze River have had positive effects on Lake Taihu including reducing phytoplankton and total nitrogen concentrations and increasing dissolved oxygen concentrations in some areas of the lake. However, because there is a net input of nitrogen and phosphorus from Yangtze River to the lake, this transfer will, on the long-term, increase nitrogen and phosphorus accumulation in the lake.
3) Pollution interception and remediation: researchers have developed programs protecting, restoring, and constructing wetlands as a way of intercepting water-born pollutants before they can enter the lake. A grass-type wetland ecosystem should have a strong assimilative capacity for pollutants and can be used to improve water quality. Wetlands, which have nutrient removal and other ecological protection functions, have been constructed as a buffer zone around the lake in order to improve lake water quality.
4) Dredging: many pollutants from urban and rural areas adhere to river particulates which then sediment out in the lake. Resuspension of these sediments results in a deterioration of water quality and allows for further distribution of contaminant sediments. Sediments can be disturbed with wave activity caused by winds and, in shallow waters, by disturbances created by boats. Dredging of these polluted sediments has been suggested as a way to further improve Taihu Lake water quality. However, the local government is challenged in the disposal of these large quantities of polluted sediment.

Summarizing and evaluating these actions, before 1998 the central government relied mainly on the strategy of zero pollution release from industrial and domestic sources. However, in practice, zero pollution is only a goal, and a never achievable goal. After finding that this strategy had limited success in improving water quality, the central government shifted its attention to water diversion. From 2002 to 2007, pumping stations diverted 5.1×10^9 m^3 of water from the Yangtze River to the lake during low lake levels (Wu and Hu, 2008). As the waters from the Yangtze River also are polluted, this method cannot provide a sustainable solution to Taihu Lake's pollution control. There also is a high risk that lake water level may be artificially heightened before the spring floods. Wetland remediation has been effective for the nearshore but less effective on offshore waters of this large lake. Dredging, as already noted, has problems with waste disposal.

Therefore, it is concluded that government strategies up until now have not been effective in addressing the problem of water quality deterioration. These existing methods have a common feature, i.e., "treatment follows pollution." This is because treatments like the water diversions, dredging and wetland construction have dealt with attempting to remedy lake water quality after the lake has been polluted by its inflowing waters. Remedies to date do not take into account that the pollution of inflowing waters varies seasonally and that a better solution may be found by restricting water inflow into the lake to periods when its quality is highest. If poor quality water is prevented from entering the lake, these treatment options should be more effective.

While industrial and municipal wastewater discharge rates remain relatively constant year-round, their concentrations in the rivers does not, i.e., inflow-river waters are heavily polluted in the dry period but pollutant concentrations are reduced during the wet (flood) period. However, as noted above, current remedial actions never restrict river inflows and so heavily polluted waters are allowed to flow into the lake year round, where they become well mixed in the lake, accumulate in lake sediments, and become increasingly difficult to remove. This is why despite a large investment in remedial action over many years, there has been no improvement of Taihu Lake water quality and algal blooms are out of control. Clearly, a new strategy for pollution prevention is needed. This new method should be cost-effective, technically feasible and eco-friendly; it also should significantly improve water quality in a short period, ca. 3–5 years.

The objectives of this paper are (1) to propose such an innovative new method for Taihu's pollution prevention; (2) to assess its feasibility of this solution for solving water pollution, flood disaster and water shortage problems; (3) to compare the proposed method with the government's methods in terms of water quality improvement, ecological issues, costs, etc.

Pollution Prevention Strategy and Suggested Measures

Taihu, as already noted, is a large shallow lake in the Yangtze delta with many rivers inflows (Sun and Huang, 1993); inflowing rivers are a major factor in deteriorating water quality. However, these same rivers can be sources of clean water during flood periods because pollutant concentrations are diluted. Based on this fact, we proposed a pollution prevention scheme that consists of a by-pass canal (BPC) with connecting sluice gates around the lake; a schematic is shown in Fig. 3. This new infrastructure can be used for flood disaster mitigation (too much water), pollution prevention (poor quality water) and to augment the clean water supply (too little and poor quality water).

The canal would have two banks. One is the existing shoreline levee that was constructed to prevent floods; after the 1991 flood, the

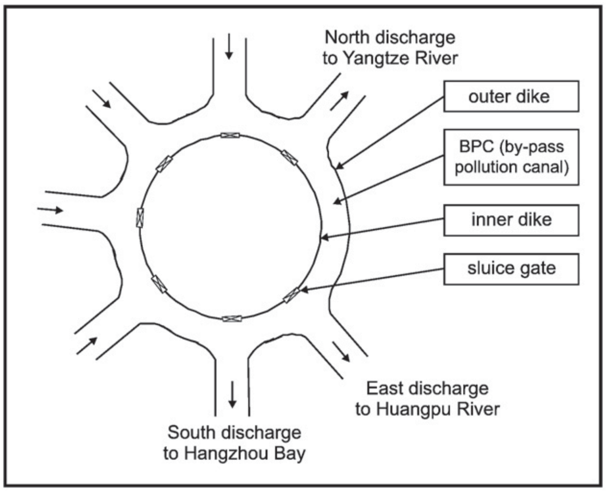

Fig. 3. Scheme of by-pass pollution canal (BPC) after Yang (2006).

levee was enhanced and strengthened. The inner bank of the canal would be built in the lake and could be constructed using dredged sediments. These two levees around the lake (shore line) together would form an artificial canal. While the two levees or dikes would be almost parallel to each other, the canal could be made wider if the flow rate were higher, e.g., near outlets relative to the upstream canal. The sluice gates would be used to regulate the floodwater.

The operation of the sluice gates can be performed as follows. In dry periods, when the inflow-rivers carry highly polluted water, the sluice gates will be closed so that all polluted water by-passes the lake and is discharged to the Yangtze River, the East China Sea and Hongzhou Bay via the three lake outlets, respectively. In the flood periods except first flushes, the sluice gates will be opened so that clean floodwater can enter the lake where it will be stored.

Feasibility Analysis of the New Scheme

Water Quality in Incoming Rivers

For every watershed, rivers always play a major role in assimilating or carrying off municipal and industrial wastewater as well as runoff from the catchment. Lakes receive a major portion of their pollutants from river inflows; therefore excessive wastewater inputs can cause serious ecological problems in the lake. However, rivers also constitute the main clean water sources to a lake. River water quality is heterogeneous spatially and temporally. In order to manage water quality in a lake, the temporal and spatial variation in water quality must be understood.

There are 219 rivers or tributaries flowing to the Taihu Lake (Hu et al., 2006), most of them come from the western part and flow out from the eastern parts via the East Taihu Bay. The river with maximum inflow is Xitiaoxi River; its annual average inflow and maximum inflow are 26.8 and 62 m^3/s, respectively. The annual average flow rate from other inflowing rivers is less than 14 m^3/s. The largest out-flowing river is Taipu River that drains lake water to the China East Sea; its mean annual outflow rate is 70.6m^3/s and the maximum outflow rate is 114 m^3/s. The second largest outflow tributary is the Wangyu River that discharges towards the Yangtze River; its annual average outflow rate and maximum outflow rate are 29.2 and 64.7 m^3/s, respectively. The outgoing flow from these two rivers accounts for almost 65% of the total outflow of Taihu Lake. The contribution to the annual averaged outflow from the third main river is less than 10 m^3/s. In Fig. 3 the outgoing river flows are simplified into three rivers.

More than 50% of rainfall in the catchment appears from June to September, so this period can be defined as the wet season, and the remaining 8 months is the dry season (Table 1). Unlike rainwater, industrial and municipal wastewater releases have little seasonal variation. The hydrograph of rainwater and wastewater is simplified as shown in Fig. 4, in which Q is the flow rate, and Q_r is the rainwater runoff, Q_w the wastewater discharge.

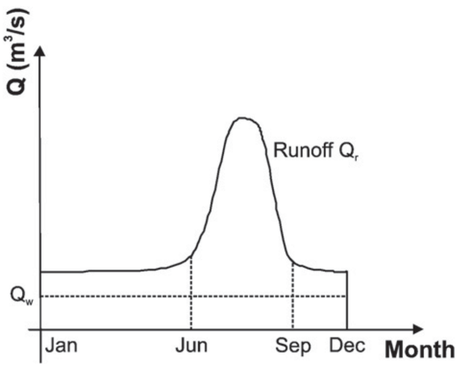

Fig. 4. Simplified hydrograph of runoff and wastewater yielded in the basin.

Integrating the runoff Q_r with respect to time from January to December, one has:

$$\int Q_r dt = V_o = 7.66 \times 10^9 \left(m^3\right) \tag{1}$$

where $V_o =$ annual water yield in the basin.

From June to September, the water volume can be estimated as half of the total water yielded from the catchment as its rainfall is half of the annual rainfall (see Table 1), i.e.,

$$\int_{June}^{Sept} Q_r dt \approx \frac{V_o}{2} = 3.83 \times 10^9 \left(m^3\right) \tag{2}$$

Similarly, the wastewater yielded in the basin can be determined by

$$Q_w \times 365(d) \times 86400(s/d) = W_o \tag{3}$$

where $W_o =$ yearly total volume of wastewater yielded in the basin and discharged to the waterways.

Currently all wastewater flows into the lake and its average concentration C_o is

$$C_o = \frac{W_o}{V_o} \tag{4}$$

In the wet season from June to September, the concentration C_1 is

$$C_1 = \frac{4W_o/12}{V_o/2} = \frac{2}{3}C_o \tag{5}$$

where $4W_o/12$ is the amount of wastewater yielded in 4 months (wet season), whilst $V_o/2$ is the amount of clean water yielded in the same period. Eq. (5) shows that in wet seasons, the water in inflow-rivers is relatively clean when compared to the water in dry seasons. An example of this can be see in Xu et al (2007) who determined that total nitrogen and nitrate plus nitrite concentrations became lower in the flood season than the dry season (Fig. 5); their measurement was conducted from October 2004 to September 2005 in a 20 m wide river flowing into Taihu Lake.

Next, the amount of wastewater entering the lake is assessed if the scheme shown in Fig. 3 is used. Normally all reservoirs or lakes have a dead volume, which is not discharged. Here we assume the Taihu Lake's dead volume is 10% of its total volume (i.e., 0.77×10^9 m^3). We assume that river water with good quality is 50% of the total water resources, that this water will be allowed to enter the lake via the sluice gates, the amount is 3.83×10^9 m^3, and the lake's storage capacity is the sum of the dead volume and the effective volume, i.e., $V = (0.77 + 3.83) \times 10^9$ $m^3 = 4.6 \times 10^9$ m^3.

It should be stressed that while the rainwater from June to September flows into the lake via sluice gates, this does not mean that

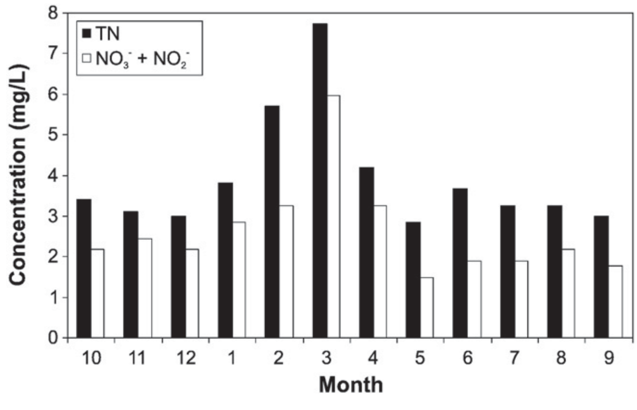

Fig. 5. Annual changes of TN and $NO_3^- + NO_2^-$.

the sluice gates will remain open for the 4-month period. Instead they will always be closed even in the flood period; they will only be opened when the river water is clean enough. Thus, the first flush of each storm event will by-pass the lake in order to prevent the non-point source pollution. In the wet season, there is an average of 46.9 rainy days (Table 1). The sluice gates will be opened, and only on these days, will the floodwater be discharged to the lake. The concentration C_{in} on these days is

$$C_{in} = \frac{46.9W_o/365}{V_o/2} \approx \frac{1}{4}C_o \tag{6}$$

It can be seen that with the aid of sluice gates and BPC, the pollutant concentration entering to the lake can be significantly reduced. In other words, only 25% of contaminants in a year will be released into the lake to mix with the clean water while 75% of wastewater yielded in a year will by-pass the lake and be discharged to the Yangtze and Huangpu rivers. While we have only discussed inflowing water concentrations, in principle, the concept can be extended to all other parameters, such as sediment inputs, BOD, TP, TN, etc.

Variations in Water Quality in Taihu Lake

Runoff and wastewater in the 219 inflow-rivers can be simplified as Q_{in} and C_{in} outflowing water can be represented by Q_{out} and $C(t)$, as shown in Fig. 6.

During time Δt, the total pollutant mass entering the lake is

$$M_{in} = \rho Q_{in} \Delta t C_{in} \tag{7a}$$

where $\rho=$ density of water, M denotes the mass of pollutant. During the same period, the total mass outgoing from the lake is

$$M_{out} = \rho Q_{out} \Delta t C \tag{7b}$$

The mass change in the lake is

$$\Delta M = \rho V \Delta C \tag{8}$$

where $V=$ lake volume (constant), ΔC is the change of concentration during the time Δt. The mass conservation principle gives the following equation:

$$V\frac{dC_{(t)}}{dt} = Q_{in}C_{in} - Q_{out}C_{(t)} \tag{9}$$

where Q_{in} can be simplified as constant in wet and dry periods, C_{in} is determined in Eq. (6), Q_{out} is the water supply rate to surrounding cities and is a constant. As Eq. (9) is a first-order linear differential equation, its solution is

$$C_{(t)} = \exp\left(-\int \frac{Q_{out}}{V}dt\right)\left(\int \frac{Q_{in}}{V}C_{in}\exp\left(\int \frac{Q_{out}}{V}dt\right)dt + c\right) \tag{10}$$

where c is an integration constant, and Eq. (10) can be further reduced into

$$C_{(t)} = \frac{Q_{in}}{Q_{out}}C_{in} + c\exp\left(-\frac{Q_{out}}{V}t\right) \tag{11}$$

At $t=0$, the concentration of lake water is C_o (equilibrium condition), thus one can determine c as follows:

$$c = C_o - \frac{Q_{in}}{Q_{out}}C_{in} \tag{12}$$

$$C_{(t)} = \frac{Q_{in}}{Q_{out}}C_{in} + \left(C_o - \frac{Q_{in}}{Q_{out}}C_{in}\right)\exp\left(-\frac{Q_{out}}{V}t\right) \tag{13}$$

As the lake water is used for industrial and municipal purposes, its outgoing discharge can be estimated by

$$Q_{out} = \frac{3.83\times10^9 m^3}{365(d)\times86400(s/d)} = 121\left(m^3/s\right)$$

Similarly in the wet seasons (46.9 days) the incoming discharge can be determined by

$$Q_{in} = \frac{3.83\times10^9 m^3}{46.9(d)\times86400(s/d)} = 945\left(m^3/s\right)$$

From Eq. (13) one has

$$\frac{C_{(t)}}{C_o} = 1.95 - 0.95e^{-2.63\times10^{-8}t} \tag{14a}$$

In the dry seasons (318.1 days), as the sluice gates are closed, $Q_{in}=0$ and from Eq. (13), one has

$$\frac{C_{(t)}}{C_o} = \exp\left(-\frac{Q_{out}}{V}t\right) \tag{14b}$$

From Eq. (14), one can predict the variation of pollutant concentration at the end of the wet and dry seasons and the calculated result is shown in Fig. 7. It can be seen that in about 3.5 years, the quality of lake water reaches another equilibrium

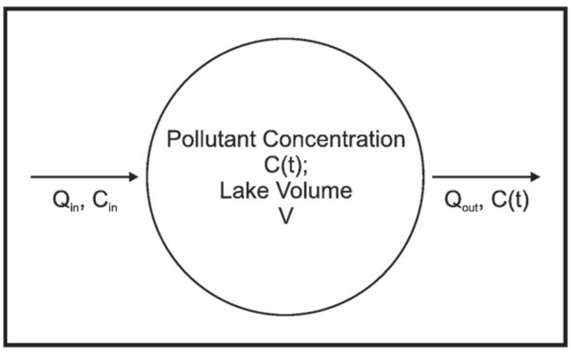

Fig. 6. Mass balance for the lake.

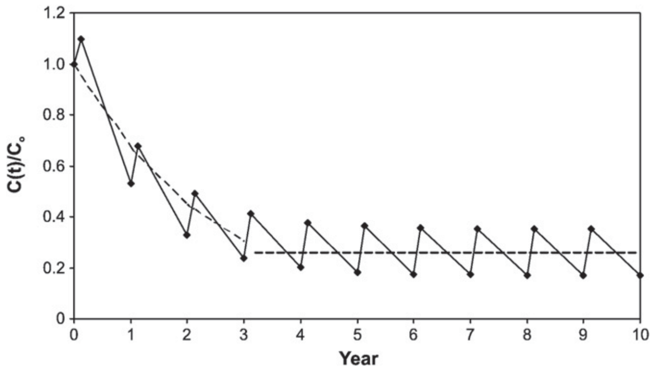

Fig. 7. Pollution concentration in wet and dry seasons after the proposed project is implemented.

condition, i.e., $C/C_o = 0.25$ and this is consistent with Eq. (6). Therefore, one can conclude that if the suggested remedial plan is adopted, algal blooms could disappear in 3–4 years time as nutrient levels decline.

Water Quality in BPC

The proposed scheme can significantly improve Taihu Lake water quality as discussed above because only clean water (or floodwater) is allowed to enter the lake. However, it may be hard to imagine that the water quality in the "by-pass canal" will be better than current lake water. This seems counter-intuitive as most of wastewater would flow in the canal surrounding the lake.

From our understanding, a slow water velocity, is one of the dominant factors responsible for the appearance of algal blooms; Soini et al (2002) found from their experiments that increases in the flow velocity decreased the bacterial densities. Higher velocities may prevent blooms from developing. Taihu Lake has a residence time of 300 days and its slow water movements create an almost quiescent environment where phytoplankton grow quickly in good light conditions; microbial particles can stick together in organic aggregates; these slow water movements together with high nutrient concentrations of nutrients contribute to the problem of algal bloom in lakes. A similar situation could also develop in the by-pass canal. However, if the residence time of water is short, ca. detention times of 3–5 days, the high velocity of the water in the by-pass canal will shear organic aggregates and transport phytoplankton into low light environments; turbulence will keep phytoplankton and aggregates dispersed. Thus, there should be no problem of algal blooms in the canal.

Higher water velocities do and can improve water quality in Taihu Lake. Spatial variations in water velocity explain the spatial variations in water quality. East Taihu Bay (Fig. 1) is a long (27.5 km) and narrow (greatest width is 9.0 km) bay located in east of Dongshan Peninsula; it connects with the West Taihu Lake at a narrow interface. East Taihu has an area of 132 km^2 (5.9% of the total Lake Taihu surface area), with an average depth of only about 1.2 m. The cross-section of East Taihu Bay is much smaller relative to West Taihu Lake, but it is the main channel draining the lake. About 70–80% of the total outgoing discharge flows from this bay; therefore the flow velocity in this bay is higher than the velocity in the West Taihu Lake as this bay is much shallower and narrower. Similarly, water quality in the East Taihu Bay is better than the quality in the West Taihu Lake even the wastewater discharge received by the former bay is four to five times of the wastewater discharge received by the latter (Yang, 2004, 2005a). This observation supports the inference that an increase of flow velocity can improve the water quality.

In the scheme shown in Fig. 3, the cross-section of by-pass canal is much smaller than that of East Taihu Bay, so the water velocity in the by-pass canal will be much higher than the velocity in the bay. Therefore, it is a reasonable to infer that the water quality as assessed from phytoplankton and organic aggregate concentrations could be better than that in East Taihu Bay.

From the above discussions, it is reasonable to conclude that the proposed scheme shown in Fig. 3 could significantly improve the water quality of Taihu Lake. Improvements are based on clean water being stored and protected by the inner levee while polluted water is retained (and concentrated) in the surrounding canal with algal blooms prevented by high flow speeds. Moreover, it is possible to further improve water quality in the canal by ecological remediation techniques and/or by flushing the wastewater in the canal using the clean water from the lake. Although high-velocity water has strong ecological self-purification capability, it is hard to accurately predict water quality in the canal; more detail research is needed in the future.

Inner pollutants

pollutants discharged from urban and rural areas accumulate in the sediment of river and lakes, and pollutants are commonly released from sediment to overlying water with disturbances induced by waves and boats. Because sediments are an important secondary pollution source, sediment dredging has been conducted as an eutrophication treatment of Taihu Lake (Zhang et al., 2008). It has been estimated that annual pollutants released from sediments could be as much as 81,000 tons of total nitrogen and 21,000 tons total phosphorus each year (Qin et al., 2005).

Suspended sediments settle to areas near the river mouths where water velocity is rapidly reduced as the river enters the lake. Thus, another threat to the secondary pollution to water quality comes from the nearshore sediment. Water quality is higher in the offshore, in part because offshore sediments are less polluted. Sediments carried by floodwater typically are relatively clean and the high flow rates can transport the sediment into the offshore to settle, i.e., far away from the shoreline. Generally sediments in the nearshore areas of lakes are the most-polluted and the offshore are less polluted.

If the by-pass canal is constructed in the nearshore region, it will significantly reduce the secondary pollution caused by sediment re-suspension because the most-polluted sediments are located in the canal and its re-suspension will not mix with the lake water, this will reduce the pollution of nearshore sediments re-suspension. Moreover, our proposed plan has yet another solution to the polluted sediment problem. While the local government has and continues to dredge the lake, they are challenged with finding locations to dispose of the dredged sediments. Initially they used the dredged sediment to pave nearby highways. However, the highways have been built and it is not cost effective to transport the sediments to more distant areas where they could be used. Our proposal may solve this problem as the dredged sediment can be used to construct the inner embankment. This is a win–win solution for the dredging project and the BPC project as well, as this solution can significantly reduce the dredging cost and the construction cost of the inner dike of BPC. Moreover, with the most polluted sediments located near the shore, the construction of an impermeable embankment will completely cut off this source of secondary pollution from this zone. Therefore, the problem of sediment secondary pollution can be prevented.

It can be seen that the strategy used in the new scheme includes: to separate the clean water from the wastewater using the sluice gates (temporal separation) and to concentrate the wastewater in the artificial canal (spatial separation). We assume that the harmful algal bloom could not occur in stagnant water if the concentration of wastewater is low enough. The quality of wastewater can be improved significantly if the flow velocity is high enough. As the most important source of drinking water for 38 cities and 34.3 million people surrounding the lake, the clean water in the lake should not be exposed to external pollution; instead it should be enclosed and protected by the dikes.

After the construction of the by-pass canal, the strategic purposes proposed by Yang (2003, 2004) can be fulfilled:

1) Clean water and wastewater should be separated spatially and temporally;
2) Clean water should be stored and protected against pollution and wastewater should be discharged as fast as possible, i.e., the detention time of wastewater in the lake should be as short as possible, whilst the retention time of clean water should be as long as possible.
3) The most effective way to treat polluted water in a lake is to maintain water movement since moving water has the capacity of self-degradation, self-decomposition and self-purification, and high turbulence shears disperse planktonic flocs and limits sessile microbial growth.

The proposed plan is totally different from the government's methods currently used in practice. The current procedure is to store dry-period wastewater in the lake but to release clean floodwater using pumps; no measures are taken for separation, protection and prevention for the drinking water. The current practice does not consider that the quality of floodwater is good; badly polluted water always appears in dry seasons. Once the contaminants mix with the clean water, it is almost impossible to treat them using any physical, chemical and biological methods as the lake is as large as 2238 km^2. Hence, it is understandable why there is no positive result to improve the water quality in the lake after 20 years of treatments and huge investment.

Mitigation of Flood Disasters

Generally, high water level results in flood disasters. Fig. 8 shows the measured water level of the lake in 1997. The highest water level (3.5 m above sea level) occurred on day 230; before that level, the water level was 3.2 m from day 181 to day 211, so the water level difference is 0.3 m (from 3.2 m to 3.5 m). The effective storage capacity for flood control is 0.67×10^9 m^3 ($=2238$ $km^2\times0.3$ m) or 14.6% of the total storage. Thus, it is apparent that Taihu Lake cannot effectively control and manage the floodwater very well and the lake has very little capacity to accommodate the peak floodwater in critical emergency. This is one of the important reasons why flood disasters often cause severe damage in this densely populated region, e.g., the floods in 1954 and 1991 (Chen and Wang, 1999).

This proposal can considerably reduce the dead storage of the lake to 10%, thus significantly increasing the effective flood-control storage of the lake. The first flush from a rainfall contains higher concentrations of non-point source pollutants from agriculture, e.g., from chemical fertilizers, pesticides, livestock and poultry and other sources; this flush is not allowed to enter to the lake but be discharged to the sea. When the peak flood wave appears, the lake still has 90% of its storage capacity which can be used for the flood control and management. On the other hand, when the sluice gates are opened at the flood peak, the velocity of flood wave propagation will be increased as very low water level in the lake increases the hydraulic gradient. Thus these actions can greatly mitigate flood disasters, store clean floodwater in the lake, and subsequently protect the lake from pollutant inputs by the operation of the enclosed dike and sluice gates.

After September, the sluice gates will be closed and the clean lake water will be available for use. Following the dry period in June of the following year and just before the onset of the rainy season, water level should be lowered to its lowest level; thus the near empty lake will have sufficient effective capacity to control the next peak flood. In other words, the lake can be operated like a reservoir with its water level lowered to reduce its storage volume and make it ready for the coming floods. The strategy of transforming a lake to a reservoir can greatly expand its capacity for flood control (Yang, 2003). Clean flood waters again will enter the lake except when measurements show that the water quality is not good enough; the hydraulic gates will be closed and inflow-rivers and the lake separated. Together this strategy will allow sufficient high quality freshwater to be kept in the lake through the drought period and until the next rainy season just like a reservoir. Data from a large number of plain reservoirs in china show that: as long as the water quality is clean enough, the algal blooms will not occur. An example is the drinking water source — Guangnan Reservoir for Dongying City at the Yellow River delta. This reservoir was formed with a 71 km long dike on the delta. It was constructed in 1986, and since that time, algal blooms have never been detected.

The lowest water level in the Taihu Lake in 1997 during dry season was about 2.3 m, and the highest water level about 3.5 m above sea level (Fig. 8). If the proposed plan is adopted, the effective volume available for flood defense is 3.83×10^9 m^3 (see Eq. (2)). Thus the estimate thickness of the effective layer is 1.7 m as the lake surface area is 2238 km^2. In other words, the lowest water level will be 1.8 m above sea level ($3.5–1.7=1.8$ m). This means that the water level in the dry season would be 0.5 m lower than the lowest water level in 1997. The lower water level at the eve of flood wave is good for flood control, but its disadvantage is that the ecosystem may be affected. In practice, the decision-maker needs to balance both of them.

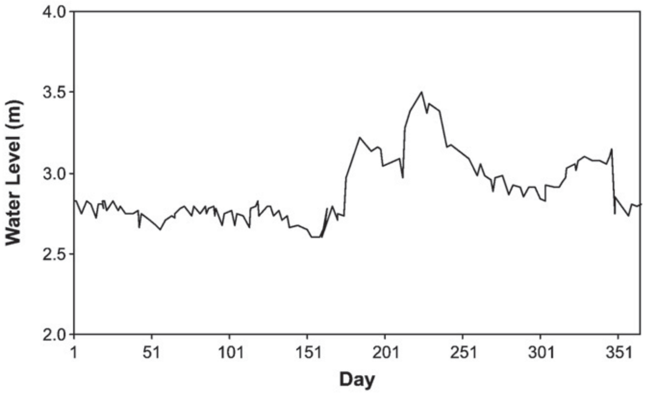

Fig. 8. Water level variation in Lake Taihu in 1997 (after Hu et al., 2006).

Augment of Water Supply

The last problem related to Taihu is its water supply. As the basin's annual rainfall is as high as 1143 mm, much higher than London (790 mm/a), Paris (566 mm/a), Beijing (630 mm/a) and San Francisco (785 mm/a), it is understandable that the basin is not short of water, but short of good quality water at proper times. Its water crisis can be solved if there is a sufficiently large reservoir to store its rainwater in wet seasons. Obviously, the water shortages are caused by improper water supply management and water quality problems because good quality water is not stored and protected properly. The above discussion clearly demonstrates that once the BPC is completed, after 3–5 years of adjustment, the water quality and seasonal water shortages problem in the basin can be alleviated.

The supply of clean water can be augmented because this BPC plan stores only the good quality of water in the lake. When the water quality in the inflow-rivers does not meet the standard, the sluice gates will be shut down, and the poor quality water forced to flow out of the lake through the canal and then into the downstream rivers. This means that almost the whole lake will be transformed into a reservoir only for clean water storage. Again, this scheme can mitigate the flood disaster as it alleviates water quality and seasonal water shortage problems.

Cost Analysis

At the end of October 2007, the government had invested 108.5 billion Yuan (≈US$16 billion) in a 5-year program designed to restore the lake's water quality and to control the level of eutrophication. In 2007, 20 billion Yuan (≈US$2.94 billion) from a special fund for pollution control provided additional financial resources. It is expected that by 2010, the cost for environmental protection will account for more than 3% of total GDP in the basin.

The length of Taihu Lake shoreline is 393 km. After the 1991 flood, China constructed a 217 km long embankment around the lake in order to defend against floods. The total construction cost was 496 million Yuan (≈US$72.9 million). This included costs for the

Table 2
Comparison of effects with/without the by-pass canal (BPC).

	Government's strategy (without BPC)	New scheme (with BPC)
Water quality	Floodwater is dumped, polluted water is stored	Floodwater (clean water) is stored, but polluted water is dumped
Mobility of the water	All stagnant, drinking water is exposed to external pollutants	Drinking stagnant water is protected, wastewater keeps moving
Non-point source of pollution	Receive 100 pollutants/sediment	Receive 25% pollutants/sediment
Lakeside Sediment pollution	A major source for secondary pollution	Completely eliminate the threat from the shore
Drinkability	Not good for drinking	Good quality for drinking
Wet land and Ecosystem	Due to siltation, wet land disappears gradually	Due to self flush, the wet land is protected
Flood control	Cannot actively control flood, water level is increased by water diversion before floods, floodwater is dumped by pumping station in flood period	Can actively control flood, water level is lowered before floods, floodwater is stored in the lake as a resource
Water level	The lake water lever is artificially maintained at high level before floods appear	Water level is lowered naturally before floods appear

construction of 172 km embankments paved for highway, 18 km of port embankments, 50.6 km of riparian foot protection by concrete slabs, 100 sluice gates, etc.

The already constructed 217 km embankment will form the levee of the external dike wall of the new canal. Construction of the inner dike wall which will protect clean water in the lake (see Fig. 3) should not exceed the external dike costs, i.e., $496/217\times\ 393=\ 898$ million Yuan (≈US$132 million). This is 0.825% of the current cost proposed by the government. If, for conservative estimation, we assume that the construction cost is five times the estimated value, then the total cost is still less than 5% of the cost by government's plan. Therefore, the new proposal is very cost effective.

Multi-objective Analysis for Ecological Sustainability

Non-point source pollution is one of the main pollution sources in Taihu Lake; it contributes more than half of total pollutants from the basin and currently, there is no effective governance program. After the construction of this canal, the problem of non-point source pollution will be solved.

Since 1854 the connection between the incidence of Cholera and the quality of water supply has been well known; pipelines have been introduced in order to protect drinking water from external pollution and waterborne disease has been significantly reduced. Our strategy of "separation, isolation and prevention of external pollution" is consistent with the idea of a pipeline, as this proposal extends the idea of "pipeline to prevent external pollution" to algal bloom control if the enclosed dike is imagined as a giant pipe. It could be expected that the incidence of algal bloom be similarly reduced.

In the current practice, floodwater is regarded as a nuisance and is pumped to Yangtze River. This proposal views the floodwater as a useful resource out of time and attempts to develop the resource. Taihu Lake basin is a developed, densely populated, low-lying region with numerous water networks, its flood control system does not keep pace with the progress of the region's rapid economic development needs. In 1991, floods led to direct economic losses of 14.1 billion Yuan (≈US$2billion) in the basin, accounting for 1.6% GDP of the basin at that year. After BPC is built, the Taihu Lake will be converted into a reservoir which can artificially adjust its storage and reduce its peak flow rate and level; thus, it can effectively mitigate the flood disasters in the basin.

Different from the government's method, the new scheme does not advocate "zero pollution" that was adopted in the basin previously and was found ineffective in reducing pollution, because the strategy of "zero pollution" had greatly retarded economic development, and the local people did not collaborate with the policy-makers. Instead, in our point of view, the discharge standard that has been implemented in other parts of China is enough for this basin and it is not necessary to implement a stricter standard for the wastewater releases. A more rigorous environmental permit system and discharge standard will force the enterprises to be relocated to the upstream of Yangtze River basin and eventually make it more difficult to control the pollution for the whole catchment. We believe that the only viable and sustainable solution is one that considers environmental protection and economic development; the enterprises responsible for the waster water releases should be confined in a small area like a industrial park, rather than disperse them elsewhere.

The new scheme can also protect the ecosystem or wetland, because the most challenging work in the lake's ecological system is the "death of the lake" due to sedimentation or wet land becoming dry land. The average depth of East Taihu Bay has been reduced by about 1 m over the past 50 years, which has resulted in the major water area of the lake becoming dry land that is now used for agriculture (Yang, 2005b). But this situation will be improved after the canal is built, because like wastewater, most sediment will no longer deposit in the lake, but be retained in the canal and be discharged to the downstream rivers. As the canal's cross-section is small, flow velocity will be high to keep sediments' suspended and for the self-flushing; thus the lake's life span will be extended. This is a notable advantage for the scheme's ecological sustainability. As this canal is constructed inside the water body, excavation and relocation are unnecessary, so its disturbance to the society is minimal. The comparison of sustainability with/without the canal is shown in Table 2.

Conclusions

Due to rapid economic development, the Taihu Lake basin is facing serious water-related problems, such as water pollution, floods, water quality and seasonal water shortages. The issue of the water environment in the basin has already attracted serious attention at national and international levels.

This paper reviewed the government's strategy for environmental management, and concluded that its technical path is that "treatment follows pollution", i.e., it lets wastewater from the basin mix fully with the lake's water and then uses physical, chemical and biological methods to treat the polluted (or fully mixed) lake water. This strategy, which has been used for the last 20 years, has failed to control pollution in Taihu Lake.

This paper presented a new scheme for pollution control, i.e., allow high quality floodwater in the lake, where it will be retained, but prevent low quality polluted water from entering the lake by means of a by-pass canal. Our feasibility analyses show that it only should take 3.5 years to solve the environmental problem after the scheme is implemented because the plan can separate clean water inflow from polluted wastewater inflow; clean water is stored in the lake but polluted water bypasses the lake and is discharged.

The plan's sustainability is also analyzed with results showing that it is a win–win solution from an economic and ecological perspective. Its construction cost is less than 5% of the cost of government's current pollution control plan. In addition, the new scheme can greatly mitigate the flood disaster and extend the lake's life span by reducing sedimentation. Thus the new proposal is environment friendly, cost effective and sustainable.

Acknowledgment

The authors would like to thank the editorial board for their valuable comments and suggestions, especially to reviewer #1 and the editor.

References

Chen, Z.Y., Wang, Z.H., 1999. "Yangtze Delta, China: Taihu Lake-level variation since the 1950s, response to sea-level rise and human impact". Environ. Geol. 37 (4), 333–339.

Ding, L., Wu, J.Q., Pang, Y., Li, L., Gao, G., Hu, D.W., 2007. "Simulation study on algal dynamics based on ecological flume experiment in Taihu Lake, China". Ecol. Eng. 31, 200–206.

Guo, L., 2007. "Doing battle with the green monster of Taihu Lake". Science 317, 1166.

Hu, W., Jørgensen, S.E., Zhang, F., 2006. "A vertical-compressed three-dimensional ecological model in Lake Taihu, China.". Ecol. Model. 190, 367–398.

Hu, W., Zhai, S., Zhu, Z., Han, H., 2008. "Impacts of the Yangtze River water transfer on the restoration of Lake Taihu". Ecol. Eng. 34, 30–49.

Jin, X., Wang, S., Yan, P., Wu, F.C., 2006. "Phosphorus fractions and the effect of pH on the phosphorus release of the sediments from different tropic areas in Taihu Lake, China". Environ. Pollut. 139, 288–295.

Ling, D., Wu, J.Q., Pang, Y., Li, L., Gao, G., Hu, D.W., 2007. "Simulation study on algal dynamics based on ecological flume experiment in Taihu Lake, China". Ecol. Eng. 31, 200–206.

Pu, P.M., Hu, W.P., Wang, G.X., Zhang, S.Z., Hu, C.G., Yan, J.S., 1998. "The new strategy for improving the aqua-ecological environmental in Taihu Lake Basin, China. How can we solve the problem of lack of qualified water and deterioration of environment and natural resources in Taihu Lake basin". J. Lake Sci. 10, 47–58.

Qin, B.Q., Hu, W.P., Chen, W.M., 2002. "Process and Mechanism of Environmental Changes of the Taihu Lake. Chinese Science Press, Beijing, pp. 97–98 (in Chinese).

Qin, B.Q., Zhu, G.W., Zhang, L., Luo, L.C., 2005. "Large shallow lake sediments inter source nutrients released model and its estimation methods — Lake Taihu as example". China Sci. Ser., D, Earth Sci. 35 (Suppl. II), 33–44 (in Chinese).

Qin, B.Q., Wang, X.D., Tang, X.M., Feng, S., Zhang, Y.L., 2007. "Drinking water crisis caused by eutrophication and cyanobacterial bloom in Lake Taihu: cause and measurement. Adv. Earth Sci. 22 (9), 896–906 (in Chinese).

Soini, S.M., Koskinen, K.T., Vilenius, M.J., Puhakka, J.A., 2002. "Effects of fluid-flow velocity and water quality on planttonic and sessile microbial growth in water hydraulic system". Water Res. 36, 3812–3820.

Sun, S.C., Huang, Y.P., 1993. "Taihu Lake". Ocean Press 19-21 (in Chinese).

Wu, H.Y., Hu, Y., 2008. "Maintaining healthy rivers and lakes through water diversion from Yangtze River to Taihu Lake in Taihu Basin". Water Sci. Eng. 1 (3), 36–43.

Xu, M., Ren, R.L., Liu, M.S., 2007. "Annual changes of water quality in an upstream river of Taihu Lake". J. Nanjing Forestry University 31 (6), 121–124.

Yang, S.Q., (2003). An means of increasing flood control capacity of the lakes." China, Patent registration number: 03130017.0, (in Chinese)

Yang, S.Q., 2004. The Global and China's water crisis and solution's in the 21th Century. Tianjin University Press.

Yang, S.Q., 2005a. Strategy of "remediation follows pollution" causes pollution out of control in lakes. China Sci. Paper Online 30 (8), 1–18 (in Chinese).

Yang, S.Q., 2005b. "Transformation of lakes into reservoirs can greatly mitigate the flood disasters in middle and lower reaches of Yangtze River". China Sci. Paper Online 1 (9), 1–14 (in Chinese).

Yang, S.Q., (2006). "A method for pollution control in large water bodies", China Patent No. 03129750.1.

Yang, M., Yu, J.W., Li, Z.L., Guo, Z.H., Burch, M., Lin, T.F., 2008. "Taihu Lake not to blame for Wuxi's woes". Science 319, 158.

Ye, W.J., Liu, X., Tan, J., Li, D., Yang, H., 2009. Diversity and dynamics of microcystin—Producing cyanobacteria in China's third largest lake, Lake Taihu. Harmful Algae 8 (5), 637–644.

Zhang, T.X., Wang, X.R., Jin, X., 2007. "Variations of alkaline phosphatase activity and P fractions in sediments of a shallow Chinese eutrophic lake (Lake Taihu).". Environ. Pollut. 150, 288–294.

Zhang, L.M., Xia, M.F., Zhang, L., Wang, C., Lu, J.L., 2008. "Eutrophication status and control strategy of Taihu Lake". Frontiers Environ. Sci. Eng. China 2 (3), 280–290.